Applied Energy 179 (2016) 1048–1061

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Development of an integrated energy benchmark for a multi-family housing complex using district heating

Jaewook Jeong, Taehoon Hong [*], Changyoon Ji, Jimin Kim, Minhyun Lee, Kwangbok Jeong

Department of Architectural Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 03722, Republic of Korea

HIGHLIGHTS

- The energy benchmarks for MFHC using district heating were developed.
- We consider heating, hot water, electricity, and water energy consumption.
- The benchmarks cover the site EUI, source EUI, and CO_2 emission intensity.
- The benchmarks were developed through data mining and statistical methodologies.
- The developed benchmarks provide fair criteria to evaluate energy efficiency.

ARTICLE INFO

Article history:
Received 19 October 2015
Received in revised form 4 June 2016
Accepted 17 July 2016
Available online 25 July 2016

Keywords:
Energy benchmarking
Energy use intensity
CO_2 emission intensity
Multi-family housing complex
Decision tree
Operational rating system

ABSTRACT

The reliable benchmarks are required to evaluate building energy efficiency fairly. This study aims to develop the energy benchmarks and relevant process for a multi-family housing complex (MFHC), which is responsible for huge CO_2 emissions in South Korea. A database, including the information on building attributes and energy consumption of 503 MFHCs, was established. The database was classified into three groups based on average enclosed area per household (AEA) through data mining techniques. The benchmarks of site energy use intensity (EUI), source EUI, and CO_2 emission intensity (CEI) were developed from Groups 1, 2, and 3. Representatively, the developed benchmarks of CEI for Groups 1, 2, and 3 were 28.17, 24.16, and 20.96 kg-CO_2/m^2 y, respectively. A comparative analysis using the operational rating identified that the developed benchmarks could solve the irrationality of the original benchmarks from overall database. In the case of the original benchmarks, 93% of small-AEA-groups and 16% of large-AEA-groups received lower grades. In the case of the developed benchmark, the upper and lower grades in Groups 1–3 were both adjusted to 50%. The proposed process for developing energy benchmark is applicable to evaluate the energy efficiency of other buildings, in other regions.

1. Introduction

Since global warming became a worldwide concern, many countries, including South Korea, have struggled to reduce greenhouse gas (GHG) emissions and energy consumption [1]. Their efforts have been stimulated through the enactment of the *United Nations Framework Convention on Climate Change* in Rio de Janeiro, Brazil, in 1992, and the *Kyoto protocol* in Japan in 1997 [2,3].

In South Korea, approximately 25% of the overall GHG emissions are released by the building sector. Moreover, 53% of GHG emissions from the building sector belong to residential areas. Especially, multi-family housing complexes (MFHCs), of which over 48% of households live in, are responsible for over a half of the overall GHG emissions in the residential building sector [4,5]. Thus, it is important to reduce the energy consumption and GHG emissions of MFHCs. Accordingly, South Korea established its national carbon emission reduction targets (CERTs) to reduce its GHG emissions by 37% below its business as usual level until 2030, and, particularly, by 25.7% below its business as usual level until 2030 in its domestic industries [6]. Toward this end, various policies, such as the spread of green buildings and renewable energy technologies, and the reinforcement of energy saving design guidelines for building sectors have enforced and prepared.

To reduce GHG emissions and energy consumption generated in the operation phase of buildings, it is necessary to measure the amount of GHG emissions and energy consumption generated in comparison to other buildings [7–10]. These actions can be defined as energy benchmarking [11,12]. In New York City, the database on

---

[*] Corresponding author at: Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 03722, Republic of Korea.

E-mail address: hong7@yonsei.ac.kr (T. Hong).

http://dx.doi.org/10.1016/j.apenergy.2016.07.086
0306-2619/

Nomenclature

AEA	average enclosed area per household	*CHAID*	chi-squared automatic interaction detector
ANN	Artificial Neural Network	*DT*	decision tree
ANOVA	analysis of variance	*EUI*	energy use intensity
BECCS	Building Energy Consumption Certification System	*GHG*	greenhouse gas
CART	classification and regression trees	*MFHC*	multi-family housing complex
CEI	CO_2 emission intensity	*MRA*	multiple Regression Analysis
CERT	national carbon emissions reduction target	*TEA*	total enclosed area

all types of buildings, of which the gross floor area is larger than 50,000 square feet, has been established. The energy benchmarking has been conducted based on the database, however, the building attributes which can affect the energy efficiency in the same building type are not considered [13]. In South Korea, the *Building Energy Consumption Certification System* (BECCS) for the energy benchmarking on MFHCs has been implemented on a pilot basis, and will be officially used in 2016 [14]. The BECCS, however, has a number of limitations. First, it only evaluates the site energy use intensity (EUI), or the final energy consumption data of building residents, but it does not evaluate source EUI and CO_2 emission intensity (CEI). Second, it does not consider the type of heat source used in MFHCs, such as district heating or individual boiler. Since energy efficiencies vary, depending on the type of energy sources used, the amounts of energy consumption of buildings can be also variable according to the type of energy source used. While lighting and appliances in MFHCs are operated by electricity, heat energy sources are divided in several types. Thus, the energy performance of MFHCs should be separately evaluated by heat sources.

Therefore, this study aims to develop the integrated energy benchmark for MFHC using district heating, and the process model using data-mining techniques is proposed to determine the energy benchmark with scientific manner. The developed benchmarks cover: (i) site EUI for measuring final energy consumption by building residents during the operation phase of buildings; (ii) source EUI for measuring consumption of the total amount of raw fuel required to operate buildings [15]; and (iii) CEI for measuring the amount of GHGs emitted during the operation phase of buildings.

The methodologies for evaluating the building energy efficiency can be generally divided into two types: one using building energy simulation based on the energy demand calculation considering the characteristics of a building and the other using data-mining techniques based on the building's actual energy consumption. The former allows a detailed analysis by setting various conditions related to the energy consumption of buildings. Since this methodology requires various and detailed information on the length of residence and the current conditions of electronic-equipment use, it entails too much time and effort [16,5]. While the building energy simulation is proper for analyzing individual buildings or households, it is not proper when considering the scale of an MFHC. In addition, energy benchmark should be determined based on the actual energy consumption of buildings. Thus, data-mining techniques are more appropriate for this study.

Multiple Regression Analysis (MRA), Artificial Neural Network (ANN), and Decision Tree (DT) have been frequently used with data-mining techniques to evaluate the energy consumption of buildings. MRA is a statistical method most widely used in predicting energy consumption as it is simple, and it allows the influence of various input variables on the target variable to be easily determined via the regression coefficients. MRA does not, however, offer a clear causal mechanism [17–19]. ANN produces good prediction performance even if the variables have a nonlinear relationship. Nevertheless, ANN has a hidden layer called black box, and so it cannot easily result in a logical interpretation [20–22]. Moreover, though MRA and ANN are appropriate methodologies in predicting value based on test cases, they are not suitable in determining the benchmarks for MFHCs. DT is a classifier that is depicted in a flowchart-like tree structure. DT has been widely used to represent classification models for its comprehensible nature in resembling human reasoning and its ability to construct models automatically from labeled examples. Moreover, since DT clearly shows how to reach a decision by graphical representation, it allows statistics analysts to easily understand and use its contents [16,17,23]. Therefore, this study uses the DT technique with data mining techniques to develop the benchmarks.

Toward this end, this study was carried out as follows: (i) The database, including annual energy consumption data in 2014 and various attributes to explain MFHCs, was established through data filtering and conversion; (ii) The energy benchmarks for site EUI, source EUI, and CEI were developed based on the proposed process using data-mining and statistical analysis like correlation analysis, analysis of variance (ANOVA), and post hoc test; and (iii) A comparative analysis of the original and the developed benchmarks was conducted to verify the efficiency of the developed benchmarks. Fig. 1 shows the framework of this study.

2. Materials and methods

2.1. Establishment of database

2.1.1. Data collection

District heating is a system for distributing heat generated by centralized plants for residential and commercial heating requirements, such as space heating and water heating. District heating plants can have higher efficiencies and control pollution better than individual boilers. According to previous research, district heating with combined heat and power is the cheapest method of cutting carbon emissions, and emits the lowest carbon footprints of all fossil generation plants [24]. As shown in Table 1 and 26.2% of MFHCs have used district heating in South Korea. Moreover, 82% of MFHCs using district heating are located in Seoul and its suburban cities [25]. The application of district heating is steadily increasing due to its high energy efficiency and low environment impact. Thus, this study focuses on the MFHC using district heating in Seoul and its suburban cities, as shown in Fig. 2.

The energy consumption data used during the operation phase of buildings are required for developing the energy benchmarks. Thus, this study collected the 2014 energy consumption data (including heating, hot water, electricity, and water) of MFHCs in Seoul and its suburban cities from the Korea Apartment Management Information System. And the data of MFHCs built within the period from 2003 to 2013 were collected to avoid the influence of selective facility retrofit in old MFHCs. Furthermore, various